

Workshop on Microwave Cavity Design for Axion Detection

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Livermore Valley Open Campus

Book of Abstracts

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Microwave Cavity Axion Searches - I / 0**Greetings and Welcome****Microwave Cavity Axion Searches - I / 54****Axion Dark Matter Detection with Microwave Cavities - Overview of Challenges**

Author: Gianpaolo Carosi¹

¹ *Lawrence Livermore National Laboratory*

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In this talk I will present an overview of the axion dark matter haloscopes that use microwave cavities to resonantly enhance the conversion rate of axions to potentially detectable levels. I will layout the number of design challenges facing experimental efforts moving forward.

Microwave Cavity Axion Searches - I / 55**Cavity Design considerations for ADMX**

Here we will present a historical context for the design considerations that lead to the ADMX cavity system from Phase 0 - Phase I.

Microwave Cavity Simulations - I / 51**Introduction to RF-Structures and Their Design**

Author: Frank Krawczyk¹

¹ *Los Alamos National Laboratory*

The numerical design chapter of the class addresses two topics: (1) Numerical Methods that include resonator design basics, introduction to Finite Difference, Finite Element and other methods, and (2) Introduction to Simulation Software that covers 2D and 3D software tools and their applicability, concepts for problem descriptions, interaction with particles, couplers, mechanical and thermal design, and finally a list of tips, tricks and challenges.

Microwave Cavity Simulations - II / 42**ACE3P for RF structure simulation**

Author: Daniel Bowring¹

¹ *Fermilab*

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RF codes such as Comsol and CST Microwave Studio are powerful tools but they have some limitations. Most notably, simulation throughput is limited by the availability of expensive (and therefore typically scarce) solver seats. Furthermore, high-fidelity geometry meshing may be difficult.

SLAC has developed ACE3P, a 3D parallel code for RF structure simulation that runs on the National Energy Research Scientific Computing Center (NERSC). Simulations may be run relatively quickly in batch mode with extremely high geometry fidelity. We present a brief introduction to ACE3P, some example simulations from other experiments, and an assessment of its utility for ADMX.

Superconducting Microstrip Resonators - I / 50

Superconducting Microresonators

Author: Jonas Zmuidzinas¹

¹ *California Institute of Technology*

Superconducting microresonators have attracted substantial attention over the past fifteen years due to a number of applications including photon detection, particle detection, and quantum devices. Our understanding of the behavior of these devices has advanced substantially during this period, particularly with regard to the influence of two-level systems on the dissipation and noise observed in these resonators, as well as nonequilibrium and nonlinear effects observed in the superconducting materials. Nonetheless, there are still significant gaps in our understanding in several areas, and there remains substantial opportunity for improvement and innovation as well as application to new problems. This presentation will outline both the recent developments and the remaining challenges in this field.

Superconducting Microstrip Resonators - II / 48

Simulation of Superconducting Qubit Devices Using COMSOL

Author: Nick Materise¹

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Over the last decade, superconducting qubits have emerged as strong candidates for a scalable quantum computing architecture. These devices deliver coherence times approaching milliseconds and basic coherent quantum logic operations have been demonstrated. First order models for superconducting qubits follow lumped circuit element representations, capturing a large portion of their behavior for practical operation. Despite their continued improvement in coherence times, quality factors, and measurement techniques, the qubits and their resonant readout circuitry still suffer from environment-induced noise. Current models of noise involve phenomenological explanations where uniformly distributed harmonic oscillators and two level systems simulate thermal excitations and intrinsic defects. To further investigate the microscopic sources of noise, we are developing simulations using COMSOL Multiphysics, a finite element solver with a broad range of capabilities including high frequency electromagnetics, thermodynamics, and any arbitrary physics described by differential equations. In this talk, we discuss some of the COMSOL modeling techniques currently applied in our study and the future direction of our larger qubit modeling effort.

Superconducting Microstrip Resonators - II / 64

Microstrip Resonator Design work at LLNL

Author: Matt Horsley¹

¹ *LLNL*

We will present initial simulation work for microstrip resonators at LLNL.

Quantum Limited Axion Cavity Amplifiers - I / 70

A Varactor Tuned Microstrip SQUID amplifier for axion searches

Author: Sean O'Kelley¹

¹ *UC Berkeley*

Here we will overview the SQUID amplifier that has been developed for the ADMX experiment.

Quantum Limited Axion Cavity Amplifiers - I / 49

Josephson Parametric Amplifiers: Theory and Application

Author: Andrew Eddins¹

¹ *UC Berkeley*

Measurement of signals consisting of small numbers of microwave photons per unit bandwidth requires multiple amplification stages so the signal can be efficiently detected by room temperature electronics. However, even the lowest-noise commercially available microwave amplifiers add the equivalent of tens of photons of noise, making them insufficient for the amplification of single- or sub-photon signals. Recent interest in measuring photon-level signals from superconducting circuits has motivated the intensive development of Josephson parametric amplifiers (JPAs). Consisting of Josephson junctions shunted by a capacitor to form a nonlinear resonator, a typical JPA provides large gain (~20 dB) with nearly quantum-limited noise performance over instantaneous bandwidths of many MHz (depending on frequency band) that can be tuned over an octave. These devices have enabled a variety of experiments with superconducting qubits, including high-fidelity readout, quantum feedback, and observation of individual quantum trajectories. They also provide a valuable tool for the field of microwave quantum optics through their ability to generate squeezed states of the EM field. In this talk, I will discuss the operating principle and design considerations of a JPA circuit, their typical usage in qubit measurement, and their potential application to the detection of dark matter.

Microwave Cavity Motion Control / 77

Piezoelectric Tuning of Microwave Cavities for Axion Searches

Author: Christian Boutan¹

¹ *University of Washington*

The Axion Dark Matter eXperiment (ADMX) searches for dark-matter axions by looking for their resonant conversion to microwave photons in a strong magnetic field. In the event that ADMX rules out axions in the 500MHz - 2GHz frequency range, new technologies and cavity geometries will need to be explored to find higher mass axions. ADMX Sidecar is a higher frequency pathfinder experiment that uses a miniature resonant cavity to search for axions in the 3.5GHz-6GHz frequency range. The Sidecar cavity sits on top of the main ADMX cavity and relies greatly upon piezo motors for tuning and for antenna coupling. Here I discuss the progress of this experiment and give an update on our success with piezoelectric tuning/coupling.

Microwave Cavity Motion Control / 60

A Prototype Piezoelectric Drive System for ADMX

Here we will present work on a prototype rotary piezoelectric drive system to adjust tuning rods in the ADMX experiment.

Microwave Cavity Axion Searches - II / 43

4-9 GHz Cavity Development at CAPP

Author: Harry Themann¹

¹ *Center for Axion and Precision Physics*

Corresponding Author: themann@ibs.re.kr

I will present our experiences with developing expertise at cavity design. We were given a chance to run parasitically in an 8T magnet with a 60mm bore. This drove our choice of frequency regime. Because of the fixed geometry of the refrigerator and magnet we were required to have all mechanisms and actuators in close proximity to the dilution refrigerator and in a fringe field of 100-300G. We took this as an opportunity to also develop experience and expertise using piezo actuators.

Microwave Cavity Axion Searches - II / 62

The ADMX-HF Experiment

Author: Karl van Bibber¹

¹ *UC Berkeley*

Here we will present an overview of the ADMX-HF experiment at Yale University and discuss the lessons learned in the development of a 4-6 GHz microwave cavity which has recently gone through its first commissioning data taking.

Axion (& Paraphoton) Microwave Cavity Searches - III / 56

Open Cavity Resonators - Project Orpheus

Author: Gray Rybka¹

¹ *University of Washington*

Overview and progress of the open cavity resonator concept.

Axion (& Paraphoton) Microwave Cavity Searches - III / 45

Cross-spectral measurement techniques for axion cavity searches

Author: Stephen Parker¹

Co-author: Michael Tobar¹

¹ *The University of Western Australia*

Corresponding Author: stephen.parker@uwa.edu.au

The cross-spectrum of two measurements rejects uncorrelated signals, while retaining those that are correlated. Here we present some fundamental concepts of cross-correlation measurements and how they can be applied to axion cavity searches. One technique allows for improved resolution when observing the intrinsic thermal noise of cavities by rejecting uncorrelated amplifier noise. A different technique allows the spectrum outputs of two spatially well-separated cavities to be effectively combined.

We will also present a brief status report of a cavity-based search for ~26.6 GHz CDM axions.

Axion (& Paraphoton) Microwave Cavity Searches - IV / 46

Novel Microwave Cavities for Precision Measurement and Testing Fundamental Physics.

Author: Michael Tobar¹

¹ *The University of Western Australia*

Corresponding Author: michael.tobar@uwa.edu.au

At the University of Western Australia we have a long history of developing high-Q cavities and transducers at microwave frequencies for applications for precision measurement, frequency standards, quantum information applications and testing fundamental physics. The latter includes hidden sector photon and axion experiments. Types of resonators include high-Q dielectric whispering gallery resonators, TE and TM mode resonators, reentrant cavity resonators, including new multipost cavities.

A broad overview of the cavity types and uses will be given, with particular focus on applications to axion and hidden photon sector experiments.

Axion (& Paraphoton) Microwave Cavity Searches - IV / 76

Searching for Hidden Photons

Author: Jeremy Mardon¹

¹ *Stanford*

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A “hidden photon” is a possible new particle, similar to the photon but with a small mass and with only a tiny coupling to electrically charged particles. Searches for hidden photons – whether as dark matter or as a new force carrier – have a great deal of overlap with corresponding axion searches. However, they tend to be significantly easier for two reasons: 1) static B-fields are NOT required, and 2) the astrophysical constraints are much weaker, making the allowed part of parameter space easier to reach. I will briefly review the landscape of hidden-photon theory and searches.

Low Frequency Axion Searches / 73

Slow Wave Cavity Axion Search

Author: Gianpaolo Carosi¹

¹ *Lawrence Livermore National Laboratory*

Corresponding Author: carosi2@llnl.gov

Here we outline the concept of using reactive endcaps to lower the frequency of a cylindrical cavity.

Low Frequency Axion Searches / 52

LC Circuit Based Low Frequency Axion Search

Author: Nicole Crisosto¹

¹ *University of Florida ADMX*

A status update of prototype testing for LC circuit based axion searches will be presented. This will include initial results for various inductor geometries and tuning mechanisms.

Low Frequency Axion Searches / 79

Reentrant Cavity for Low Mass Axion Search

Author: Akash Dixit¹

Co-authors: Aaron Chou ²; Andrew Sonnenschein ²

¹ *University of Chicago*

² *Fermilab*

Corresponding Author: avdixit@uchicago.edu

Simulations and initial measurements of a reentrant cavity designed to explore lower frequencies in a fixed magnet bore volume.

Increasing Cavity Quality Factor / 44

Novel Aluminum-based High-Q Cold RF Resonators for ADMX

Author: Katsuya Yonehara¹

Co-authors: Aaron Chou¹; Akash Dixit²; Daniel Bowring¹

¹ *Fermilab*

² *University of Chicago*

Corresponding Author: yonehara@fnal.gov

Improved aluminum refining techniques now provide high-quality, cost-effective high-purity aluminum samples. The high-purity aluminum will be better resonator material than copper because of its extremely low resistivity and high thermal conductivity at cryogenic temperature in strong magnetic fields. We will show material properties of high-purity aluminum and demonstrate possible improvement of the aluminum based ADMX resonator.

Increasing Cavity Quality Factor / 80

Primer on Superconducting Radiofrequency Cavities

Author: Daniel Bowring¹

¹ *Fermilab*

This overview will outline the motivation and concepts behind superconducting radio-frequency microwave cavities, primarily in the context of accelerator cavities.

Increasing Cavity Quality Factor / 68

Magnetic Field Limits of SRF Cavities

Author: Sam Posen¹

¹ *Fermilab*

This talk will discuss the ultimate limitations for high Q₀ operation of SRF cavities, including theoretical predictions and experimental measurements. Various SRF materials are considered and realistic expectations for maximum magnetic fields on the walls of the cavity are presented.

Increasing Cavity Quality Factor / 61

An RF sputtering system for thin film superconducting cavity R&D

Author: Maria Simanovskaia¹

¹ *UC Berkeley*

Here we will outline an RF sputtering system that has recently been installed at UC Berkeley with the goal of developing superconducting thin film cavities for axion searches.

Open Discussion & Presentation of New Ideas / 78

Electric Tiger

Author: James Sloan¹

Co-authors: Daniel Garrett ¹; Gray Rybka ²; Kunal Patel ¹

¹ *UW*

² *University of Washington*

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Electric Tiger is a project consisting of designing, building, and taking axion exclusion data with a prototype rectangular prism cavity. The cavity includes regions of dielectric to modify the shape of the resonant modes of the cavity in such a way that coupling to axions is enhanced. The motivation, design, and status of Electric Tiger will be presented and the outlook for the prototype and beyond will be discussed.

Active Microwave Cavities - I / 53

Cavities march in step

Author: David Tanner¹

¹ *University of Florida*

To reach high frequencies while maintaining a good B^2V , the axion detector will require either a complex multi-cell structure or the operation of a number of cavities together. In order to employ a number of cavities that are power-combined in phase, the cavity resonant frequencies will need to be identical. This talk outlines a technique developed by Pound to lock a klystron to a resonator and elaborated by Drever and Hall for locking lasers to optical resonators. This Pound-Drever-Hall method is widely used, notably by LIGO, to maintain lock of up to five resonant lengths. It employs phase modulation of the electromagnetic waves incident on the cavity, followed by mixing of the generated sidebands with the reflected carrier, and then by phase-sensitive demodulation to generate an error signal. The error signal may be used in a servo loop to adjust the cavities' resonant frequency.

Active Microwave Cavities - I / 57

Active Q Cavities

An overview of the R&D on increasing the quality factor of cavities using active feedback will be given.

Microwave Cavity Geometries - I / 58

Photonic Bandgap Cavities

Author: Samantha Lewis¹

¹ *University of California - Berkeley*

This talk will be a basic overview of Photonic Band Gap cavity design.

Microwave Cavity Geometries - I / 74

Superconducting photonic band gap structures for high-current applications

Author: Evgenya Simakov¹

Co-authors: Dmitry Shchegolkov²; Sergey Arsenyev³

¹ *LANL*

² *Los Alamos National Laboratory*

³ *MIT*

Corresponding Author: d_shcheg@lanl.gov

We report the results of recent design and testing of several 2.1 GHz superconducting radio-frequency (SRF) photonic band gap (PBG) resonators. PBG cells have great potential for outcoupling long-range wakefields in SRF accelerator structures without affecting the fundamental accelerating mode. Here we describe the results of our efforts to fabricate 2.1 GHz PBG cells with round and elliptical rods and to test them with high power at liquid helium temperatures.

Microwave Cavity Geometries - I / 59

Directly characterization of cavities with a bead-pull technique

This talk will present an overview of the bead-pull technique that is being used to characterize cavities for ADMX and ADMX-HF.

Microwave Cavity Geometries - I / 72

Progress on mode-locking cavities at U. of Florida

Here we will discuss some of the work that has been done on mode-locked cavities at U. of Florida

Quantum Limited Axion Cavity Amplifiers - II / 63

Accelerating cryogenic axion searches with one and two mode squeezed states.

Author: Konrad Lehnert¹

¹ *JILA, University of Colorado*

The search rate of cryogenic axion cavity search will soon be limited by fundamental quantum fluctuations of the microwave field. In this talk, I will describe how this noise can partially be overcome using quantum squeezing of the microwave field. In contrast to what is often thought to be the case, I will show that it is in principle possible to measure both quadratures of the axion induced microwave field without adding measurement noise.

Quantum Limited Axion Cavity Amplifiers - II / 75

Generation and Reconstruction of Propagating Quantum Microwaves

Author: ling zhong¹

¹ *Walther Meissner Institute*

Propagating quantum microwave signals are promising building blocks for quantum communication and quantum computation. In particular, such itinerant quantum microwaves can be generated by Josephson parametric amplifiers (JPAs) in the form of squeezed states. At the same time, JPAs are widely used as low noise amplifiers for the detection of microwave signals on the single photon level. In this work, we characterize the basic properties of flux-driven JPAs at millikelvin temperatures. We investigate the squeezed states generated by the flux-driven JPAs with a dual-path setup. Squeezed coherent states could be generated by sending coherent states into a JPA. Alternatively, displacement operations can be applied to squeezed states using a directional coupler. We discuss our experiments in the context of remote state preparation and quantum teleportation with propagating microwaves.

Active Microwave Cavities - II / 66

Electronic Tuning with Non-Linear Dielectrics

Author: Andrew Sonnenschein¹

¹ *Fermilab*

Corresponding Author: sonnenschein@fnal.gov

Since dielectric materials inserted into a resonator cavity cause a permittivity- There are a number of dielectric materials which might be suitable for this application, but none have been sufficiently well studied in low-temperature, high magnetic field environments. The key issue is whether the

necessary level of tunability can be achieved without prohibitively large energy dissipation. We are planning to test several materials and fabricate a prototype resonator.

Active Microwave Cavities - II / 71

Electronic Tuning & Coupling of Cavities

Author: Gianpaolo Carosi¹

¹ *Lawrence Livermore National Laboratory*

Corresponding Author: carosi2@llnl.gov

He we will present an overview of R&D efforts to employ electronic tuning and coupling of microwave cavities.

Microwave Cavity Geometries - II / 47

University of Florida High-Frequency Microwave Cavity Research

Author: Ian Stern¹

¹ *University of Florida*

Corresponding Author: ianstern@aol.com

The axion is now by far the most promising candidate for the constitution of cold dark matter and this has generated a proliferation of searches around the world. While almost all CDM axion experiments use the Sikivie haloscope method, it is clear that to reach cosmological sensitivities at higher masses, new RF techniques that go beyond the current microwave cavity designs must be advanced. The University of Florida has been conducting research to extend the usefulness of haloscope detectors to higher axion masses. Computer simulations and analytical studies have validated the theory of using periodic post arrays and regulating vanes for tuning cavities at higher frequencies. A 12-vane cavity prototype is currently under development. Mode search schemes, necessary for scanning highly crowded frequency ranges, are being explored. The Pound-Drever-Hall frequency locking technique is also being investigated using a 2-cell segmented cavity prototype. Results of the studies and status of prototype testing will be presented.

Microwave Cavity Geometries - II / 65

Resonator design strategies for high and low mass axion searches

Author: Aaron Chou¹

¹ *Fermilab*

TBD

Microwave Cavity Geometries - II / 67**Microwave and Millimeter-wave Cavity Research and Development at SLAC****Author:** Emilio Nanni¹¹ *SLAC National Accelerator Laboratory*

We present ongoing research and development in advanced microwave and millimeter-wave cavity design and fabrication at SLAC National Accelerator Laboratory. This research is primarily focused on improving the performance of accelerating structures with optimized cavity design for reducing breakdowns and increasing Q-factor, distributed coupling and improved fabrication with micro-machining and diffusion bonding. Future areas of interest will also be presented.

End of Workshop Discussion & Open Floor to New Ideas / 81**Lattice QCD Input to Axion Cosmology****Author:** Berkowitz Evan¹¹ *LLNL*

Here we describe recent work to place a lower bound on the axion mass from lattice QCD calculations.

End of Workshop Discussion & Open Floor to New Ideas / 82**Workshop Close-Out****Author:** Gianpaolo Carosi¹¹ *Lawrence Livermore National Laboratory***Corresponding Author:** carosi2@llnl.gov

End of the workshop discussion.

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The ADMX Sidecar Cavity

Overview of the ADMX Sidecar cavity system